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ROLE OF RETINOCORTICAL PROCESSING IN SPATIAL VISION

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<p>Several important image-processing functions have been proposed for the geometric distortion known as cortical (or more precisely, retinocortical) magnification.² This spatial distortion can convert the radial velocities projected on the retina by egocentric motion into uniform, rectilinear motion at the cortex. It can also convert changes of size and orientation in retinal coordinates into mere translation at the cortex. (In both cases, an image-like property is converted into a map-like property.)</p> <p>Thus cortical magnification must play an essential role in forming our stable percepts of the world around us, even as it vexes the question of how the information from different fixations within the same scene can be arranged into a single percept. Is the cortical image subsequently "undistorted,"³ just to facilitate the superposition of multiple fixations? An understanding of the image-coding functions of the primary visual cortex (V1) should help to unravel this paradox.</p> <p>Using the tools of computer vision (LISP algorithms developed on Symbolics networks), we are attempting to build a working model that includes such processes as: fixational eye movements, retinal filtering and inhomogeneity, retinocortical mapping, cortical (Gabor) image-coding, and other processes involved in the coordinate shifts needed for mapping purposes. Our goal is to understand as much as possible about the roles of these early visual processes in forming a stable percept of the world around us.</p>					
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CONTENTS

LIST OF ILLUSTRATIONS	iii
I RESEARCH OBJECTIVES	1
II CURRENT STATUS OF WORK	3
A. High-Resolution Input Images	3
B. Generality of the Model	3
C. Continuous Approximations	3
1. Inhomogeneous Spatial Filtering	4
2. Temporal Effects	4
3. Multiple Fixations	9
D. Retinocortical Mapping Functions	11
E. Retinal Ganglion Cell Spacing and Receptive-Field Sizes	13
F. Summary and Future Plans	13
III RESEARCH PERSONNEL	15
IV INTERACTIONS WITH SCIENTIFIC COMMUNITY	16
REFERENCES	17

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ILLUSTRATIONS

1	Stages of the Visual Process Considered in the Present Study	2
2	Interior Scene: Original and an Example of Inhomogeneous Filtering	5
3	Effect of Bandpass (Laplacian) Filter on the Scene Shown in Figure 2	7
4	Mixture of Low-Pass (20%) and Bandpass (80%) Inhomogeneous Filtering	8
5	Combination of Figure 4 with Two Other Inhomogeneously Filtered Images, Representing Three Different Fixations in the Same Scene	10
6	Example of a Distorted Cortical Representation, Based on the Same Scene and Fixation Point as Figure 2(a)	12

I RESEARCH OBJECTIVES

Our goal is to develop a computational model of the "front-end" stages of human spatial vision, including the retina, retinocortical pathways, and primary visual cortex V1, as illustrated schematically in Figure 1. This computational product will be a functional, *working* model, which processes the entire stimulus pattern by appropriate algorithms and which can depict its representation at each stage in graphic imagery.

To make this task more manageable, important but noncritical simplifications must be made. The model is confined to monocular, photopic, achromatic, quasi-stationary vision. Motion is considered only to the extent that normal spatial processing requires minimal eye movements. Binocularity is considered only by constraining V1 to leave room for interleaved right- and left-eye connections.

Important parts of this complex system have been modeled in other studies. Our main goal is to try to make them all fit together. In doing that, we expected to encounter problems that have not shown up before (and this is beginning to occur). Where these parts, as currently modeled, cannot be fitted together, we will try to learn why. To this end, we may modify available models, reinterpreting the literature on which they are based. If need be, we will try to devise crucial experiments to select among alternatives.

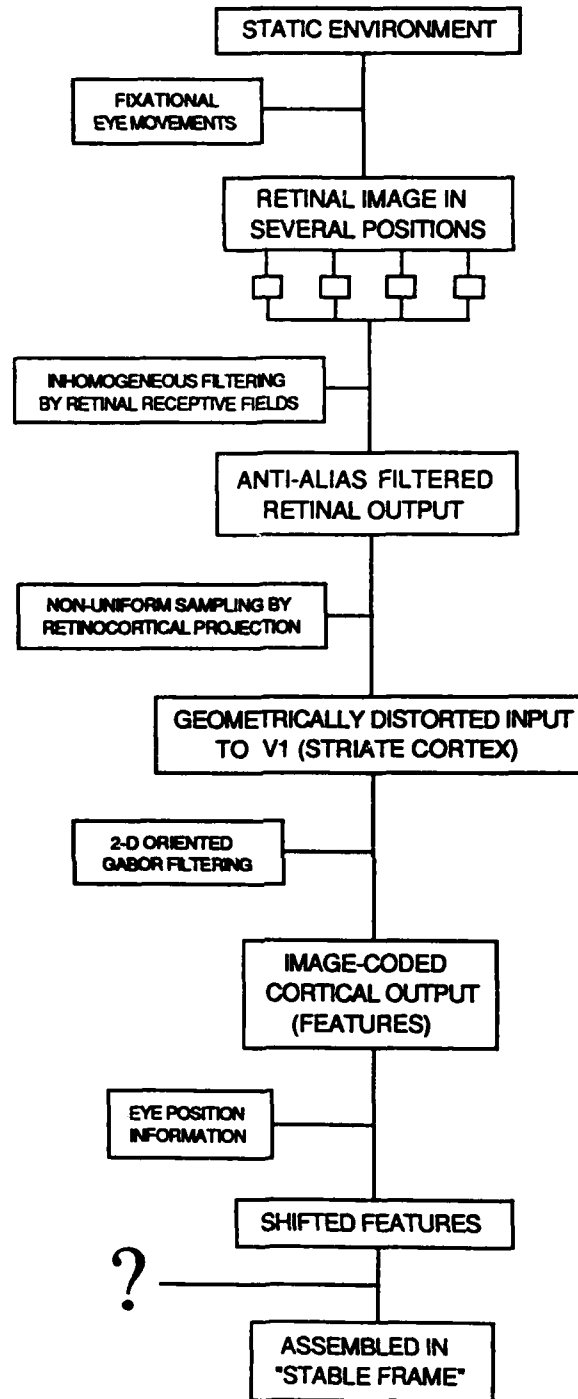


FIGURE 1 STAGES IN THE VISUAL PROCESS CONSIDERED IN THE PRESENT STUDY

We will attempt to provide representations of visual information at least through the cortical output.

II CURRENT STATUS OF WORK

A. *High-Resolution Input Images*

To simulate the "real world," we prepared several 100×125 mm (4×5 inch), fine-grain photographs of both interior and exterior subjects, taken with a 90-mm lens. The original negatives were scanned directly on a recently calibrated Optronics scanner. These images were linearized with respect to luminance and stored as a digitized (pixel) array. Digital images 4000×4000 pixels in extent, with 8 bits of gray scale, are readily produced by this procedure. The current small library of images can be expanded as needed.

B. *Generality of the Model*

In keeping with the exploratory nature of this project, our software is designed to be as modular and flexible as possible. In some of the work reported here, for example, the form of our ganglion-cell receptive fields was based on the laplacian of a gaussian (Marr and Hildreth, 1980); however, we can readily substitute any other plausible kernel for retinal filtering. A number of these functions have been proposed in the literature (Kelly, 1985, compares five of them). Likewise, the diameter of the retinal receptive fields was presumed to be minimum at the central fovea and to increase with eccentricity at a linear rate; however, other eccentricity functions can be substituted for this linear one.

We plan to use this capability to make small, quantitative changes in the functions and parameters of various parts of the model when we come to fit the parts together. This in turn should help to reveal where large, qualitative changes may be required—a main goal of this project.

C. *Continuous Approximations*

Ultimately the discrete sampling of the visual field, as performed by retinal, LGN, and cortical cells, and their interconnections (e.g., Sakitt and Barlow, 1982), constitutes a crucial aspect of our model. However, a few important issues are relatively independent of retinocortical sampling. These include

- (1) The form of the spatial-filter kernels and scaling functions used to simulate retinal inhomogeneity.
- (2) The question of how to simulate the effects of temporal changes if we don't model them directly; this and Question (1) are closely related.

We also looked at an additional question:

- (3) How many independent fixations does it take to extract adequate information from a natural scene?

These questions can be addressed by using a quasi-continuous approach in which we filter an input image at every pixel (so that the sampling limit is governed only by the resolution of the digital image). Our results with this procedure are reported in the following three subsections.

1. Inhomogeneous Spatial Filtering

A LISP program was written that convolves a high-resolution input image with a specified kernel. The size of the kernel is minimum at a selected fixation point [such as the one indicated in Figure 2(a)], and it expands linearly with distance from this point, at a specifiable rate. The appearance of the inhomogeneously filtered image depends on the form chosen for the kernel. Figure 2(b) shows the output image obtained with a low-pass (gaussian) filter. The standard deviation of the gaussian kernel in this example varied by a factor of about 4 from the fixation point to the edge of the image.

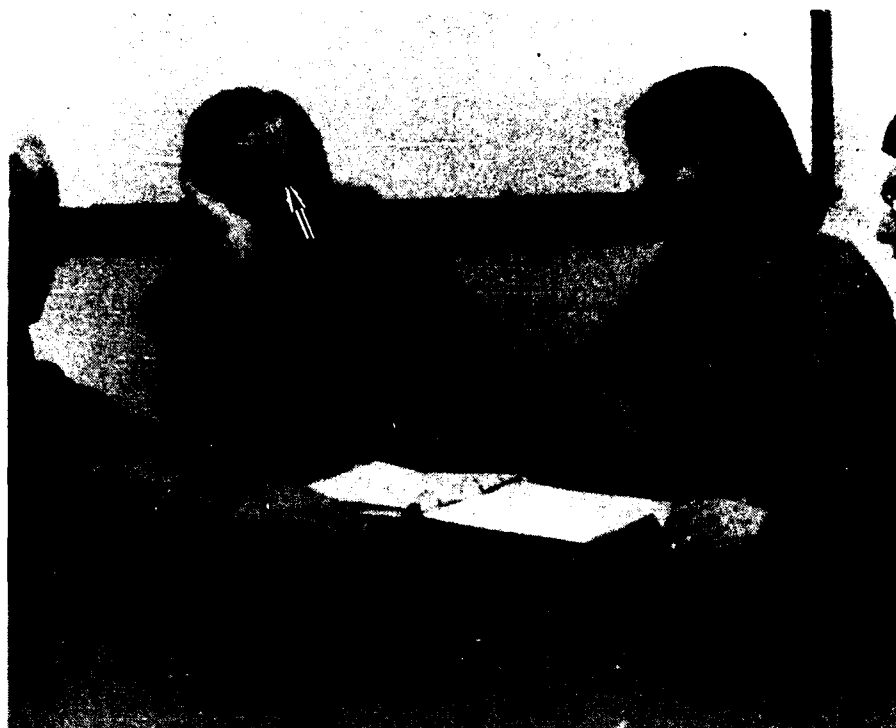
We have produced filtered outputs for several (interior and exterior) scenes with three types of kernels: low-pass, bandpass, and low-pass/bandpass mixtures. Of these, the low-pass/bandpass mixture seems to be the most realistic, for reasons discussed in the following subsection.

2. Temporal Effects

Our goal is to construct a model that concentrates on the spatial aspects of retinocortical processing. However, temporal modulation of the retinal input, by eye movements and object motion, has important effects on spatial vision. (Even when the eye is fixated on one point in a stationary scene, involuntary drift motions and microsaccades modulate the retinal input.) In order to make our results as realistic as possible, we must therefore modify the "purely spatial" responses of the model to take account of the effects of temporal modulation. Apparently these effects have not been incorporated in previous modeling attempts. The rationale for our procedures is as follows.

Responses to moving or flickering sine-wave gratings show a well-known form of reciprocity between spatial and temporal frequency responses (Kelly, 1979). The spatial frequency response shifts from bandpass to low-pass with increasing temporal frequency, and the temporal frequency response shifts from bandpass to low-pass with increasing spatial frequency. Moreover, stabilized images disappear, which implies that the temporal dc response of vision is zero.

Is the spatial dc response also zero, as in a Marr-Hildreth filter [or any of the other receptive-field filter functions compared in Kelly, (1985)]? When this type of spatial filtering is



(a) INPUT, WITH ARROW SHOWING FIXATION POINT FOR FILTERED IMAGE



(b) EFFECT OF LOW-PASS, INHOMOGENEOUS FILTER

FIGURE 2 INTERIOR SCENE: ORIGINAL AND EXAMPLE
OF INHOMOGENEOUS FILTERING

used, the resulting images contain only (bright and dark) edges on an otherwise blank (gray) background (see Figure 3). However, such effects never appear subjectively, nor in the physiological outputs of retinal ganglion cells.

At zero temporal frequency, we don't see perfectly differentiated spatial information because we don't see anything (stabilized disappearance). However, at temporal frequencies above zero, the spatial dc response is also greater than zero, increasing with increasing temporal frequency as indicated above. (At and above the peak temporal frequency, the spatial response becomes purely low-pass, just as the temporal response does above the peak spatial frequency.)

These psychophysical results are consistent with physiological properties of retinal ganglion cells (Frishman et al., 1987). If the ganglion-cell output is linear, then the zero dc response is presumably the result of balanced antagonism between center and surround. But the frequency response of the surround falls off before that of the center, so that the latter predominates with increasing frequency—either spatial or temporal. (If ganglion-cell outputs are rectified, then we must consider the balance between on-center and off-center types, but the principle is the same.)

These considerations support our basic assumption about the kind of spatial filtering that controls normal vision. We assume that the filter kernel is a mixture of bandpass and low-pass filtering, depending on the temporal frequencies present. For a stationary scene, these temporal frequencies are entirely due to eye movements, but they cover as wide a range as the spatial frequencies in the scene (because temporal frequency equals spatial frequency times the eye-movement velocity, which is the same everywhere in the image).

Note that this constitutes a kind of adaptive filter in the space domain. If the target is simply a stationary (but unstabilized) sine-wave grating, then the bandwidth of the temporal input is as low as natural eye movements permit, and result is as close to Marr-Hildreth filtering as an unstabilized retinal image can evoke. But the more complicated the scene, the broader this temporal bandwidth becomes, with its higher frequencies evoking purely low-pass spatial responses.

Nevertheless, a dilute form of spatial differentiation does occur at low temporal frequencies, producing some degree of edge enhancement. We have simulated these temporal effects by adding a low-pass spatial component to the bandpass process of Figure 3. Figure 4 shows the results of such a combination process. In this example the combined filter is weighted 4:1 in favor of the bandpass process. Although pure spatial differentiation is unacceptable, human subjects accept quite a lot of excess edge-contrast or "overshoot" in an image without noticing anything unusual. (This effect was discovered more than 30 years ago during experiments with the "synthetic highs" coding system. Perhaps some modern experiments to quantify it are in order.)

We believe we have simulated the effects of temporal modulation on spatial processing reasonably well by adding a low-pass section to the standard bandpass component, but that does not diminish the importance of the spatial differentiation component. This can be seen by comparing the results of Figure 4 with those of Figure 2(b) [or with the Kelly and Pentland (1985) pilot study], which merely used low-pass filtering.

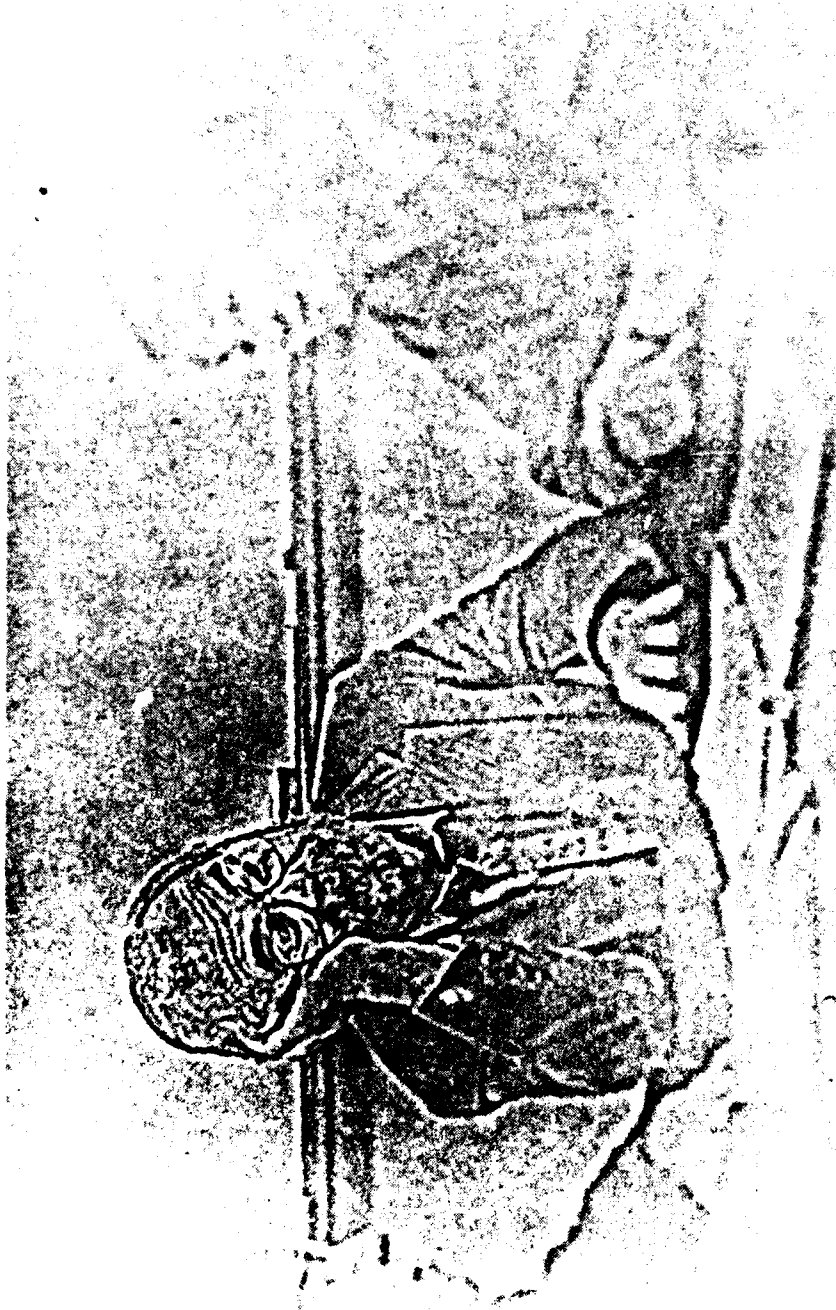


FIGURE 3 EFFECT OF BANDPASS (LAPLACIAN) FILTER ON THE SCENE SHOWN IN FIGURE 2

Notice the complete absence of gray scale.



FIGURE 4 MIXTURE OF LOW-PASS (20%) AND BANDPASS (80%) INHOMOGENEOUS FILTERING
See Figures 2 and 3.

3. Multiple Fixations

Much information is lost in the periphery of the visual field when only a single fixation is considered (as in Figures 3 and 4). To get some idea of how much of this loss may be restored by combining the information from a few well-chosen fixations, we performed the computational experiments described below. Although these experiments do not exactly simulate anything the visual process does (as far as we know), they are useful in assessing the information loss.

The visual system must have appropriate information about how eye and head movements affect the retinal coordinates of external objects, in order to compensate for these motions in such a way that the perceived environment stands still. (That information is known as the "outflow" signal.) But there is no machinery *distal* to the cortex that could use this signal to translate successive glimpses and superimpose them. That must occur at a location *proximal* to V1, where the representation has already undergone significant geometrical distortion (as discussed in Part D of this section).

Nevertheless we can justify translating and superimposing in retinal coordinates the information from different fixations on a test basis, if only to estimate the number of fixations that might typically be needed by the post-striate machinery that does combine these successive glimpses into a stable percept. (Before we try to determine how such a stable percept might actually be constructed, we need to answer the questions raised in Parts D and E about more distal parts of the system.)

Figure 5 shows an example of the information available from only three fixations in the interior scene of Figure 2(a). One of these is on the man's face [as in Figure 2(b), 3, and 4], one is on the woman's face, and one on the open book. Retinal inhomogeneity was simulated by inhomogeneously filtering each of the component images about its particular fixation point, using the 4:1 bandpass/low-pass ratio illustrated in Figure 4. We made similar tests with other scenes, including a more cluttered interior scene and the exterior of a building with many straight-line segments.

In order to treat the results as upper bounds on the information obtainable from multiple fixations, we gave considerable thought to devising an algorithm for combining these images that would not, in itself, cause any significant information loss. Each fixation-image was first filtered into a set of spatial-frequency bands by the so-called laplacian-pyramid technique, which can seamlessly blend quite different images together (Burt and Adelson, 1983). The filtered images *within each band* were then combined pixel-by-pixel, according to a formula with the following properties:

- If all pixel intensities were equal, it returned their mean.
- If only one intensity was non-zero, it returned the sum.
- For intermediate intensity distributions, the output varied smoothly between these extremes.

The resulting (pyramid) images were then combined to obtain the final result (such as Figure 5).



FIGURE 5 COMBINATION OF FIGURE 4 WITH TWO OTHER INHOMOGENEOUSLY FILTERED IMAGES,
REPRESENTING THE THREE DIFFERENT FIXATIONS IN THE SAME SCENE

See explanation in text.

We conclude from these studies that a remarkably small number of well-chosen fixations may contain enough information to produce a sharp impression of a large scene. Four fixation points seemed adequate for the most complicated images we tried.

D. Retinocortical Mapping Functions

A retinocortical mapping function maps a given point in the retina to a corresponding point in the striate cortex (V1); thus, it completely describes the geometrical distortion of the cortical representation of the visual field. By way of example, Figure 6 shows an approximate cortical representation of the scene used in Figures 2 through 4. Our model should include a mapping function that matches its physiological counterpart as accurately as possible without too much mathematical complexity.

The local change in cortical distance for a given increment of retinal distance is called the *retinocortical magnification*; in the model, this magnification factor is given by the absolute value of the differential of the mapping function. Except at the fovea, the retinocortical magnification is known to vary approximately as $1/R$, where R is eccentricity in the visual field.

If it were exactly true that the magnification varied inversely with eccentricity, then the mapping function could have a particularly simple form, in which polar coordinates at the retina (R, θ) are mapped to Cartesian coordinates (u, v) at the cortex, by the function

$$\begin{aligned} u &= \log R \\ v &= \theta \end{aligned}$$

An elegant way of describing this relation, introduced into visual physiology by Schwartz (1977), involves complex-variable theory. Let $z = x + iy = Re^{i\theta}$ at the retina, and $w = u + iv$ at the cortex. Then the idealized mapping function is simply $w = \log z = \log R + i\theta$, and the magnification is $|dw/dz|$, which equals $1/R$. This is a conformal (angle-preserving) transformation.

Unfortunately, this mapping function has a physically unrealizable singularity at $R = 0$. To fit the cortical topography in primates and other species, Schwartz (1980) adds a real constant, c , to the argument, making $w = \log(z + c)$. This gets rid of the singularity, but destroys the circular symmetry of the differential and hence of the magnification factor as defined above: The constant forces the retinocortical magnification to be greater in the vertical meridian than in the horizontal one.

Estimates of human retinocortical magnification do not show perfect circular symmetry either (particularly at large eccentricities), but the departure is in the *other direction* from that predicted by $\log(w+c)$: Horizontal magnification is greater than vertical (Rovamo and Virsu, 1979). Recent studies in the macaque also bear on this question (Tootell et al., 1982); depending on how they are interpreted, the macaque data may either support or contradict the human magnification estimates (Sakitt and Barlow, 1982; Letelier and Varela, 1984; Schwartz, 1985).

Moreover, the horizontal-to-vertical magnification ratio increases monotonically with eccentricity in the Rovamo and Virsu (1979) estimates, but in the Schwartz mapping function,

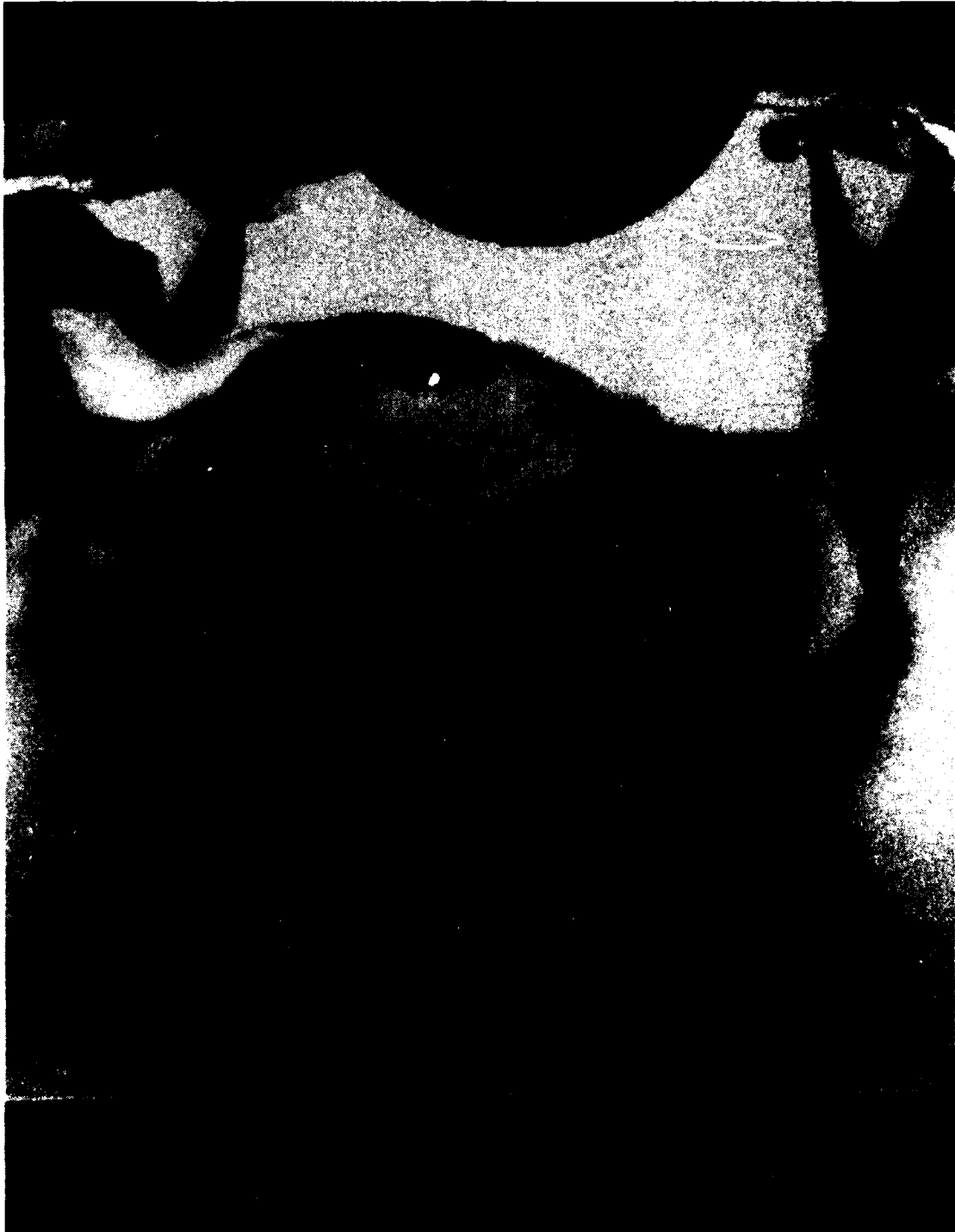


FIGURE 6 EXAMPLE OF A DISTORTED CORTICAL REPRESENTATION, BASED
ON THE SAME SCENE AND FIXATION POINT AS FIGURE 2(a)

this ratio inflects at eccentricity c , approaching unity again at greater eccentricities. Various mapping functions that are otherwise consistent with the known physiology also have this discrepancy; the problem is not yet resolved.

E. Retinal Ganglion-Cell Spacing and Receptive-Field Sizes

Once we adopt a magnification function, then we can connect a particular retinal ganglion cell to a particular cortical location. In order to take this anatomical approach, we must consider the spacing between these discrete connections and the overlap (positive or negative) of their receptive fields.

A look at two straightforward assumptions (neither original with us) may simplify the model at this stage:

- We could assume uniform sampling in Cartesian coordinates (u, v) at V1. Given a specific mapping function, this assumption completely determines the sampling distribution at the retina.
- We could postulate a polar-coordinate (R, θ) sampling distribution at the retina. If we assume uniform sampling in angle (θ) and any radial sampling distribution, then the mapping function will completely determine the sampling distribution at the cortex.

It would be appealing to try to combine the postulates of uniform sampling at the cortex and circularly uniform sampling at the retina; however, this combination is incompatible with the complex, $\log(z + c)$ mapping function.

Log-polar mapping ($\log R$ or $\log z$) combined with uniform, Cartesian cortical sampling dictates that the centers of retinal receptive fields be located at exponentially increasing eccentricities along meridians. In this case it can be shown that, if these fields are circular and their diameter is proportional to their spacing, they will overlap by a constant fraction of their area. However, the receptive fields would then become infinitesimally small as R approaches 0, which is of course not realistic (the center of a foveal receptive field must always contain at least one cone cell).

If we eliminate the singularity at $R = 0$ [by writing $u = \log(R+c)$ or $W = \log(z+c)$], the receptive-field locations are still approximately exponential outside the fovea, and their diameters are minimum at $R = 0$. In this case, however, the proportion of overlap is no longer constant. Receptive-field overlap becomes maximum at the fovea, decreasing steadily with increasing eccentricity. Hence, there may be no overlap in the periphery.

F. Summary and Future Plans

Several important questions raised in the preceding sections need to be settled before we can proceed further with implementing our model. Currently we are assessing alternative postulates and the restrictions they imply for various properties of the visual system. It is already apparent that we will be forced to modify traditional models of some parts of the system if we are to fit them into a consistent picture of the whole.

Far from being a "hang-up," this is a gratifying situation that confirms the value of doing the present kind of study. We were aware of the difficulties of constructing a stable percept out of geometrically distorted cortical representations, but we did not strongly expect to uncover other significant inconsistencies, especially in the well-studied details of retinal sampling and cortical projection. Having arrived at this point in the first year of the project, fortunately, we plan to pursue these inconsistencies to the best of our ability.

III RESEARCH PERSONNEL

D.H. Kelly, Principal Investigator (Visual Sciences Program)

Grahame Smith, Senior Computer Scientist (A.I. Center)

John D. Peters, Research Assistant.

IV INTERACTIONS WITH SCIENTIFIC COMMUNITY

The PI has been informally conferring on the subject of this study with visual scientists and other peers for several years. Most of these talks occur at the ARVO and OSA meetings, which he regularly attends. There are also informal exchanges between our vision group at SRI and other local vision groups, such as those at Stanford, Berkeley, and Smith-Kettlewell.

Particularly relevant to the present report have been two occasions on which this project was discussed with Dr. Eric Schwartz of NYU during the past year. Dr. Kelly and Dr. Schwartz met for this purpose during the AFOSR Vision Meeting at Annapolis in December. They talked about each other's work and agreed to try to meet again. In April 1988, Dr. Smith and Dr. Schwartz met at the SPIE meeting in Orlando, and discussed various questions about modeling the visual system. We plan to foster this common involvement during the next two years of this project.

Also at the SPIE meeting, Dr. Richard Juday of Johnson Space Center presented his results on an image sensor whose output is the log-polar transform of the sensed space (see Section II-D). This appears to be a device that would, for the first time, allow rapid experimentation with various "cortical" algorithms. In discussion with Dr. Smith, Dr. Juday expressed interest in having other projects, such as ours, make use of the device. We will pursue this connection to determine whether it could be of benefit to our study.

Because this is the first year of a new project (and a new direction for the PI), we have not yet generated formal publications or oral presentations (other than at Annapolis) that could be credited to this study. We expect that some of the topics treated above can be developed for publication during the second year.

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